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Optimization of planning structure in irrigated district considering water footprint under uncertainty

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ABSTRACT

Agricultural water and land, which are intricately related, are the two most critical resources for food production. However, the sustainability of agricultural water and land resources is faced with challenges due to intensive human activities and climate change. This paper builds crop water footprint model under uncertainty, and evaluates regional crop (rice, maize and soybean) blue and green waterfootprint under different probability. On this basis, the water footprint characteristics and differences of crops were analyzed. Then, an optimization model of crop planting structure with the objectives of minimum blue water footprint and the maximum agricultural net benefit was constructed and Monte Carlo simulation method was used to solve the model. The model can take into account the crop water footprint at different probabilities, enabling decision makers to combine years of information to make better decisions. Then, the model was applied to the Hulan River Irrigation District, and three scenarios were designed to analyze the optimal planting structure under different conditions. Under different scenarios, the optimization results have certain differences, but overall, increasing the area of crop cultivation, especially rice, has a good role in promoting regional agricultural development. Due to the optimization of the planting structure, the net benefit of the irrigation area increased by 7%, 15% and 5% in each of the three scenarios. Solutions are valuable for producing scientific alternatives that help decision makers determine the water and soil relationship management policies they need.

1. Introduction

With the accelerating process of industrialization and urbanization, the contradiction of people increasing, arable land shrinking, the problem of water shortage is becoming more and more prominent. The demand for water from various sectors of society and economy will bring tremendous pressure on agricultural water requirement. Due to China's unique natural geographical features, the spatial and temporal distribution of water resources is extremely uneven, therefore, agricultural development depends largely on irrigation. The irrational use of agricultural water resources and the low efficiency of irrigation water have become the biggest obstacle to the sustainable development of agriculture in China Liu et al. (2017). Therefore, improving water use efficiency in agriculture is the fundamental way to solve the shortage of agricultural water resources. Under the premise of water saving in agriculture, through the adjustment of agricultural planting structure and the optimal allocation of agricultural water resources, it is of great significance to maximize the use of agricultural water resources and the economic benefits for the sustainable development of regional agriculture Zhang et al. (2014).

Inspired by the theory of virtual water, the Dutch scholar Hoekstra proposed the concept of water footprint based on the concept of ecological footprint in 2002 Renault (2002), Chapagain and Hoekstra (2002), Hoekstra (2003), Chapagain et al. (2006). The water footprint can truly reflect the water resources of a person, a region or a country. Real demand and occupancy, by measuring the water footprint reflects the pressure of human resources on water resources, and provides a useful basis for scientific use of limited water resources Chapagain et al. (2006). However, the previous research on the model of water footprint is a deterministic model, which can only indicate the regional water footprint under a certain state, and cannot fully reflect the reality. Therefore, this paper establishes an uncertain crop water footprint model, which can represent the blue-green water footprint of different crops at different frequencies.

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At present, there are some scholars are researching planting structure optimization based on water footprint Zhang et al. (2015), Pongpinyopap and Mungcharoen (2015), Noori et al. (2015), but, these optimization method is usually based on the deterministic system parameters and optimization model. However, in the actual situation, many parameters are not deterministic constants in the water resources system, which inevitably bring about some errors or uncertainties in the application. Qin et al. (2007), Gaivoronski et al. (2012), Miao et al. (2014). Because these factors more or less contain uncertainty, there are great difficulties in mathematical treatment. In many cases, the model is simplified to transform multiple uncertainties into a single, deterministic model. However, this process will also pay a certain price, and it cannot reflect the actual situation more objectively. Therefore, it is necessary to use the uncertainty optimization theory to optimize the system. It can more accurately reflect the objective world and obtain more reliable optimization results and it is of great practical significance to study and apply the uncertainty optimization theory Xie and Huang (2014), Carrero-Parreño et al. (2017), Beh et al. (2017) In order to describe the problem of agricultural water resources management under uncertain conditions in more detail, a calculation method based on probability and statistical theory methods, such as Monte Carlo (MC) simulation method, can be selected. Matsui et al. (2005), Wang and Sloan (2011). At present, the application of MC in the management of agricultural water resources is still rare. As an effective assessment tool, MC can be used more widely in the uncertainty of agricultural water resources Hunt and Miles (2009), Graveline et al. (2012), Houska et al. (2014).

The aim of this study is to introduce uncertain water footprint to crop optimization of planting structure to improve the irrigation district agricultural water resources management, mitigate the contradiction between supply and demand of water resources and realize the sustainable development of agriculture. This study includes the following aspects: (1) Establishing a Water Footprint Model Based on uncertainty. (2) Calculate the blue water footprint and green water footprint of different crops in the irrigation district under different probability. (3) Uncertain water footprint was introduced into the plant structure optimization model and three optimization scenarios were set up (4) Analyze optimization results under different scenarios, and the model is tested by applying to a real world study in northeast China.

2. Development of methodology

2.1. Overview of the problem

The optimization of planting structure can help us to better allocate water and land resources in the region to achieve higher benefits and save more water resources. The introduction of water footprint analysis method can refine the type of water consumption and reflect the human's role in agricultural production. The demand and occupancy of water resources provide a whole new perspective for water resources management; uncertainty theory can restore a system that is usually simplified, breaking through the limitations of deterministic methods on data representation. Thus, this paper aims to introduce WF analysis method to irrigation district optimization of planting structure under uncertainty. The study frame is as shown in Fig. 1.

2.2. Evaluation method of crop water footprint under uncertainty

The concept of water footprint was proposed by Hoekstra et al., in 2002 Chapagain and Hoekstra (2002), Hoekstra and Chapagain (2007) based on the study of virtual water, which refers to the total amount of direct and indirect water contained in the products and services consumed by people in a region (ie the virtual water contained in these products and services). For crops, "Green water" is the water produced by the precipitation infiltrating into the soil during the crop production process and can be absorbed and utilized by the plants; "blue water" is the water stored in rivers, underground aquifers, reservoirs and lakes consumed during the production of crops. It is mainly used for irrigation agriculture. Different crops have different degrees of utilization of green water during the growing season. Evaluation of blue water and green water footprint can improve the utilization rate of water resources in the region, save the amount of blue water and guide the adjustment of crop planting structure and comprehensive utilization of water resources. Conventional deterministic method to calculate water footprint is as follow:

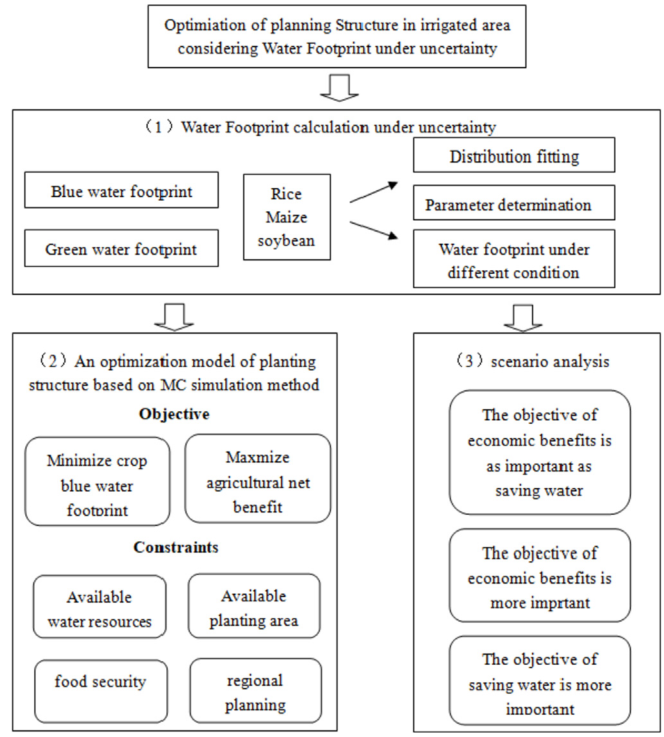

Fig. 1. System framework.

$$WF = WF_{green} + WF_{blue} \tag{1}$$

$$WF_{green} = CWU_{green}/Y = 10 \cdot \sum_{d=1}^{n} ET_{green}/Y \tag{2}$$

$$WF_{blue} = CWU_{blue}/Y = 10 \cdot \sum_{d=1}^{n} ET_{blue}/Y \tag{3}$$

Simulate crop evapotranspiration by water demand of crop, which assumes crops grow under optimal conditions, that is, crop water demand is fully satisfied.

$$ET_c = CWR = \sum_{d=1}^{n} K_c \cdot ET_0 \tag{4}$$

$$\frac{0.408\Delta \cdot (R_n - G) + 900\gamma/(T+273) \cdot U_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34U_2)} \tag{5}$$

K_c is determined by the crop characteristics and the average evapotranspiration effect of the soil. Calculations of the soil from the CROPWAT database can be made by determining crop growth and latitude and longitude positions.

The effective precipitation was calculated by multiplying precipitation by an effective coefficientLi et al. (2018). If precipitation was less than 50 mm, then the coefficient was 0.9; if precipitation was greater than 50 mm but less than 150 mm, then the coefficient was 0.75; and if precipitation was greater than 150, the coefficient was 0.7.

The demand for irrigation is determined by the difference between crop water requirement and effective precipitation. If the effective precipitation is greater than the crop water requirement, irrigation demand is 0, and the green water evapotranspiration is evapotranspiration, which is equal to the smaller value of total crop evapotranspiration and effective precipitation. Blue water evapotranspiration is farmland irrigation water evapotranspiration, which is equal to total crop evapotranspiration minus effective precipitation, and the expression is:

$$ET_{blue} = \max\left(0, ET_c - P_{eff}\right) \tag{7}$$

$$ET_{green} = \min\left(ET_c, P_{eff}\right) \tag{8}$$

In traditional models, the water footprint is usually a deterministic value. However, in fact, the meteorological factors in the calculation process are random, so the effective rainfall and ET are all random parameters with uncertain properties. Therefore, the water footprint is also a random variable. Using different years of meteorological data, calculate the water footprint of each year. Statistical analysis software was used for data fitting to find the type of distribution that the data was subject to, and the blue and green water footprints of different crops at different frequencies were calculated. The specific steps are: (1) Consolidate annual weather data and crop data; (2) Calculate the blue water footprint and green water footprint of different crops using the above formula.; (3) Use statistical analysis software to perform data distribution and fitting to find suitable distribution types and find the distribution parameters; (4) Calculate crop blue-green water footprint at different frequencies according to distribution type and parameters.

2.3. An optimization model of planting structure based on MC simulation method

2.3.1. Model development

The water footprint method can be used to comprehensively and clearly describe the characteristics of crop water consumption, and can be used as a guide to develop sustainable cropping and suitable use of water resources by adjusting cropping structure based on the water footprint in arid land. Considering the different characteristics of blue water footprint and green water footprint of different crops, this paper established a multi-objective regional crop planting structure optimization model under uncertainty. The optimization objectives are to maximize agricultural net benefit and minimize regional crop blue water footprint. We will make efficient use of limited agricultural water resources and get optimized planting structure of irrigated area. The Monte Carlo method can be used to better solve the model and the specific model is as follows:

Objective functions:

$$\max f = a_n \frac{f_1^*}{f_{1\max}} - b_n \frac{f_2^*}{f_{2\min}} \tag{9}$$

$$f_1^* = \sum_{i=1}^{I} \sum_{j=1}^{J} \left[(P_j Y_j - C_j) S_{ij}^* - CW \right] \tag{10}$$

$$f_2^* = \sum_{i=1}^{I} \sum_{j=1}^{J} WF_{blue\ j}^* \cdot S \tag{11}$$

(1) Planting area constraints:

$$\sum_{j=1}^{J} S_{ij}^* \le SA_i, \quad \forall i \tag{12}$$

$$\sum_{i=1}^{I} S_{ij}^* \le SC_j, \quad \forall j \tag{13}$$

(2) Blue water resources available constraints:

$$\sum_{j=1}^{J} WF_{blue\ j}^* \cdot S_{ij}^* \cdot Y_j \le AW_i, \quad \forall i \tag{14}$$

(3) Green water constraints:

$$\sum_{j=1}^{J} WF_{green\ j}^* \cdot S_{ij}^* \cdot Y_j \le MW_i, \quad \forall i, j \tag{15}$$

(4) Regional water supply capacity constraints:

$$\sum_{j=1}^{J} MA_{ij} \cdot S_{ij}^* \le MW_i \cdot \eta, \quad \forall i, j \tag{16}$$

(5) Yield constraints:

$$\sum_{i=1}^{I} S_{ij} \cdot Y_j \ge Y_{\min j} \tag{17}$$

2.3.2. Model solution

The Monte Carlo method, also called random sampling or statistical test method, belongs to the branch of computational mathematics Matsui et al. (2005), Graveline et al. (2012). It is a method of using random numbers (or more commonly pseudorandom numbers) to solve many computational problems. The problems solved are connected with the same fixed probability model, and statistical simulation or sampling is performed with the computer to obtain the approximate solution of the problem. To symbolically indicate the statistical characteristics of this method, it was named after the Casino Monte Carlo Wang and Sloan (2011), Houska et al. (2014), Lv et al. (2018). The calculation flow chart is shown in Fig. 2.

In this paper, the uncertain parameters are crop blue and green water footprint. Ascertain their distribution function, according which to generate random numbers, and the number of simulation can be set as 220. Multiple sets of randomly generated input parameters are respectively optimized to obtain the corresponding optimal solution.

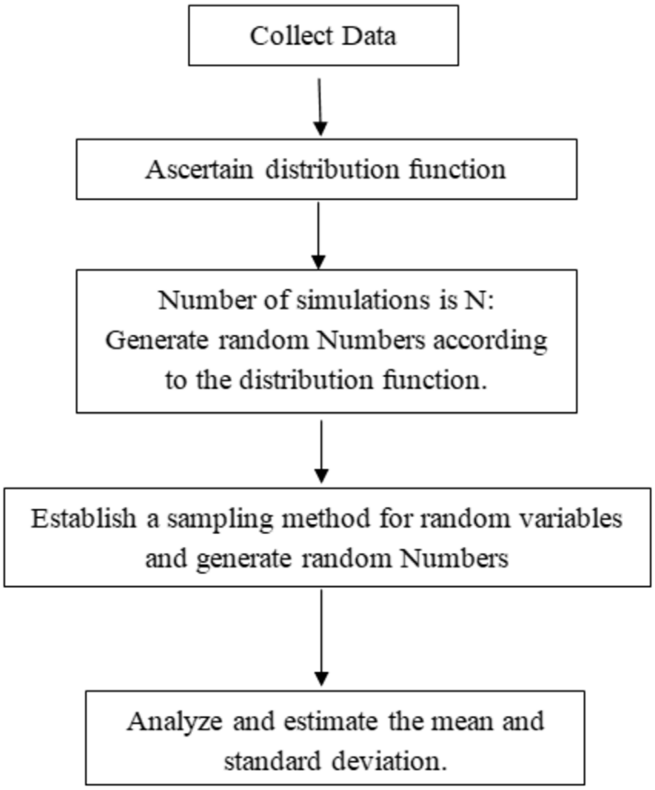

Fig. 2. Monte carlo simulation flow chart.

3. Application

3.1. Study area

Hulan river irrigation district is located in Qingan county which is in the central part of Heilongjiang province, at the west of Xiaoxing'anling. The irrigation district stands on the impact plain of hulan river, which is in the middle and upper reaches of the Hulan river basin. Geographical coordinates is east longitude 125°55′-128°43′and north latitude 45°52′-48°03′.The Hulan river irrigation district in Qingan county belongs to a semi-arid and semi-humid continental monsoon climate with moderate seasonal climate. In the spring, the weather is dry with little rain, the wind is cold and warm. The summer is hot and rainy, and the winter is cold. In the autumn, the weather cools quickly and easy to frost. The average annual precipitation is 545.3 mm, and the change range is between 450 and 700 mm. Precipitation is unevenly distributed during the interannual years, and the average annual surface evaporation is 664.5 mm (measured in 20 cm evaporating pans) with a range of 462–873 mm. The average temperature for many years is 1.7 °C, and the effective accumulated perennial temperature which is more than or equal to 10 °C is 2518 °C. The county's average annual frost-free period is 128 days, up to 150 days and at least 114 days. The average annual sunshine hours is 2577 h. Due to the influence of hilly mountains and forested areas, the temperature in the southwest is higher and the north is lower. The annual growth of crops from the end of April to September 20 is 1211 h, and the annual solar radiation is 110 kcal/cm^2. The freezing period is 6 months and the maximum freezing depth is 1.8–2.1 m.

The Irrigation district divides the Hulan river irrigation district into two sub-regions: The south including the Heping subarea, Jianye subarea and the Liuhe subarea. The north includes the Fengtian subarea and the Laomo subarea. Heilongjiang Province is China's first agricultural province, and Hulan River Irrigation District is a typical irrigation district in Heilongjiang Province, so the study is representative of the irrigation district. Food crops including rice, maize and soybean occupy most of the planting area of Hulan River irrigation district, among which rice is the main crop to plant because of higher net benefits. Most of the water consumption in the Hulan river irrigation district is used for agricultural irrigation. Therefore, optimizing the allocation of available land and water resources for food crops is of great significance to the region (Fig. 3).

3.2. Data collection

In this study, the data needed for the model are as follows: effective precipitation, evapotranspiration, related crop parameters, subarea parameters and weight scenarios for objective functions.

3.2.1. Effective precipitation and evapotranspiration

Effective precipitation and evapotranspiration are basically random, and most of them have significant changes for different frequencies. Therefore, it is necessary to estimate the interval values of at different frequencies to reflect the randomness. The time series of all these parameters was 55 years (1954–2008) and they were collected from the hydrological station and the meteorological network. The effective precipitation was calculated by multiplying precipitation by an effective coefficient as mentioned in section 2.2. For crop evapotranspiration (ET_c), the daily reference evapotranspiration (ET_0) was estimated using the FAO56 Penman-Monteith method. The FAO56 Penman-Monteith method was adopted because it was considered to be the basic method for calculating the reference ET_0 of the Food and Agriculture Organization of the United Nations in 1998. It has strong theoretical and computational precision. The FAO56 Penman-Monteith method is widely used around the world. Climate factors include average temperature, minimum temperature, maximum temperature, average wind speed, sunshine duration, and average relative humidity are the basic input data for this method. The monthly and annual values of ET_0 are derived by summing up the daily value (Fig. 4).

3.2.2. The related crop parameters

The related crop parameters in this study include market prices, acreage, yield per unit area, planting costs, and water costs. These parameters come mainly from yearbooks, reports, websites, field surveys and previous studies. Obtain crop area data and production per unit area from the plan report and yearbook. The other parameters mainly include the proportion of groundwater irrigation, the proportion of irrigation in each irrigation district of the corresponding river, the utilization coefficient of canal system and field water, and the hydraulic parameters. All of these parameters in the study were deterministic indicators from the planning and design report of the Hulan river irrigation district. The values of channel and field irrigation utilization factors in each region were 0.5 and 0.8, respectively. The surface water transport loss coefficient, field water loss, and rainfall infiltration coefficient were 0.49, 0.10, and 0.08, respectively.

3.2.3. Subarea parameters

Other parameters mainly included irrigation proportion of groundwater, irrigation proportions for each irrigation district from the corresponding rivers, utilization coefficient of canal system water and field water, and hydraulic parameters. All these parameters were deterministic in this study that came from Planning and Design Report of Hulan river irrigation district.

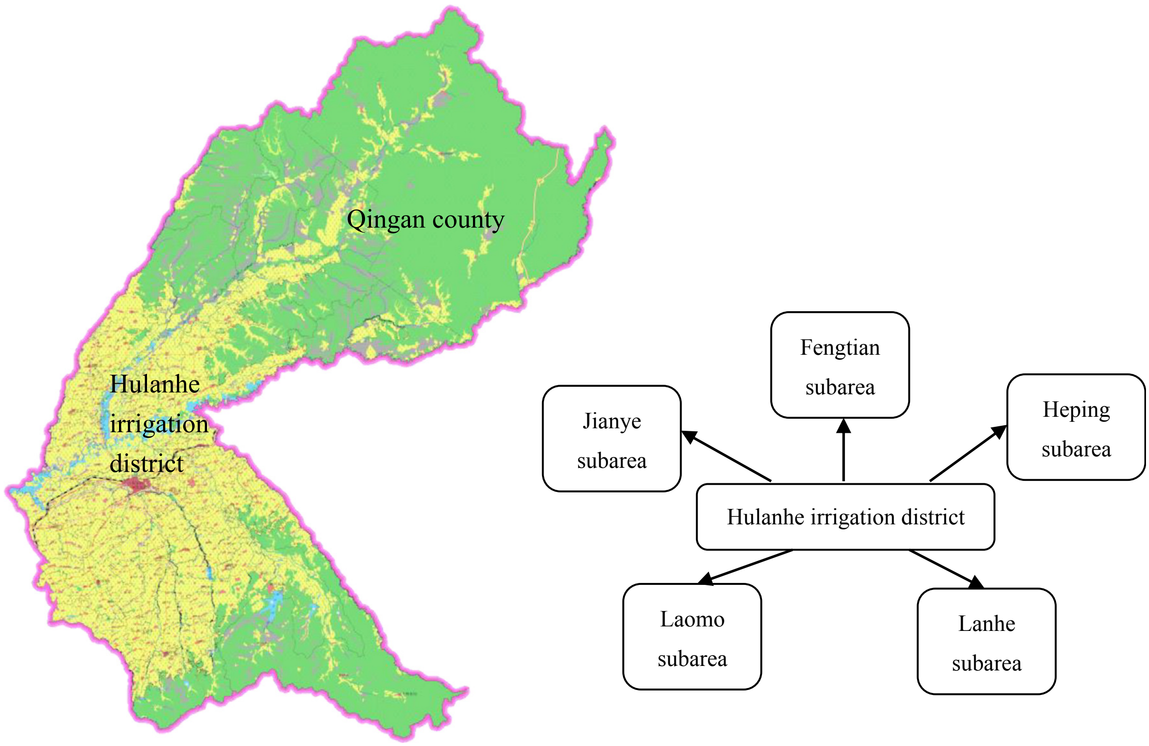

Fig. 3. Schematic diagram of the study area.

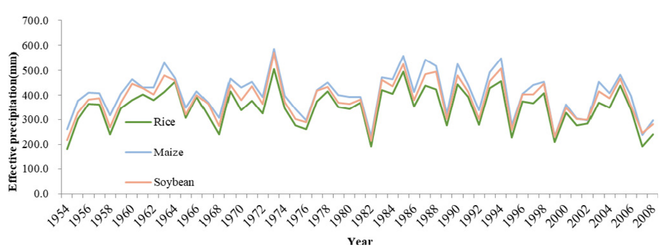

Fig. 4. Effective rainfall during the growth period of different crops.

3.2.4. Weight scenarios for objective functions

In this study, linear weighted sums were used to determine the weights of the two goals. Referring to the relevant literature, try a variety of weights within the selected range, and after comparison, select a relatively appropriate group. Three scenarios were set up: Scenario 1 mentions the equal importance of the two targets; Scenario 2 mentions the situation where the economic benefits goal is critical; Scenario 3 mentions the situation where the water saving goal is critical.

Data can be seen in Tables 1–4:

3.3. Results and discussion

3.3.1. Results of crop blue and green water footprint under uncertainty

Calculate crop unit blue and green WF in different years, and results are shown in Fig. 5.

Table 1
K_c for different crops.

K_c	May	Jun	Jul	Aug	Sep
Rice	0.38	0.78	1.34	1.06	0.45
Maize	0.3	1.2	1.2	1.2	0.8
Soybean	0.4	1.15	1.15	1.15	0.7

The unit blue WF of soybean is the largest, changing in the range of 0.8–1.6 kg/m^3. The blue WF of the rice unit varies from 0.2 to 0.6 kg/m^3, and the maize is relatively small, which is about 0.3–0.4 kg/m^3. Soybean unit green WF is higher, and the change range is larger, at 0–0.6 kg/m^3 interval, and the maize small, on a scale of 0–0.1 kg/m^3. The unit green WF of rice changes from 0 to 0.4 kg/m^3.

Using statistical analysis software to test data distribution pattern, and results show it can be described by normal distribution. The unit blue and green WF of different crops are fitted, and parameters of normal distribution are shown in Table 5. Then, calculate crop blue and green WF at different frequencies according to distribution type and parameters, and results are shown in Table 6.

3.3.2. Results of optimization of planting structure

According to the MC simulation method, the uncertain parameters (crop WF) are randomly generated according to their respective distribution characteristics, and the input parameters are respectively optimized to obtain the corresponding optimal solution. Then, this paper would conduct a comprehensive analysis and discussion on these optimization solutions.

The objective function values are normalized to be distributed in the 0–1 range. The water consumption, net benefit, and the processed objective function values of the Hulan river irrigation district are analyzed to make a three-dimensional scatter plot, as

Table 2
Planting area status quo of different crops.

Planting area (hm^2)	Rice	Mazie	Soybean
Fengtian	1085	275	139
Heping	6628	114	85
Jianye	958	24	24
Laomo	4079	1365	983
Lanhe	2021	877	615

Table 3
Basic economics data for different crops.

	Rice	Mazie	Soybean
Sale price (Yuan/kg)	2.82	2.87	5.45
Production cost (Yuan/hm2)	9526	5010	4980
Yield per unit (kg/hm2)	9100	10101	2643
Net benefit per unit (Yuan/hm2)	15,805	23,980	9424

Table 4
Weighting coefficients of different scenarios.

Weighting coefficient	Scenario 1	Scenario 2	Scenario 3
Benefit objective	0.5	0.75	0.25
Blue water footprint objective	0.5	0.25	0.75

shown in Fig. 6. It can be seen from Fig. 6 that the distribution of the optimization points in the three scenarios is not the same, which shows that the tendency of setting the model weights has a greater impact on the optimization results of the model.

In scenario 1, the distribution of the data balls is relatively scattered in the projection surface of relative values of the objective function and the net return, and projection surface of the relative values of the objective function and the water consumption. Most of the projection points are in the center and have a circular distribution. The crop water consumption range is 115×10^6-$130 \times 10^6\,m^3$ and the net benefit range is 320×10^6-370×10^6 Yuan. When the relative value of the objective function is relatively large, the water consumption and net benefit are neither extremum, but in the middle position, which is due to contradictions of water consumption and net benefit, when the income is large, the water consumption is usually large, too. It can be seen in the projection surface of water consumption and net benefit. When the weight coefficient given to the benefits and the water saving objective are the same, the optimization results of the model would balance the contradiction between the two and take the value in the middle.

In scenario 2, the distribution of the data balls is nearly in a straight line in the projection surface of relative values of the objective function and the net return, and projection surface of the relative values of the objective function and the water consumption. The crop water consumption range is 120×10^6-$140 \times 10^6\,m^3$ and the net benefit range is 340×10^6-370×10^6Yuan, both of them are higher than scnario 1. When the relative value of the objective function is relatively large, the water consumption and net benefit are also large, and the tendency in two projection surface are both monotonically increasing. In other words, high relative value of objective function means high water consumption and high net benefit.

In scenario 3, the distribution of the data balls is similar to scenario 2, however, the tendency is absolutely opposite. It is because the allocation of high weight coefficient of water consumption, that model tend to get less net benefit to save more water. The crop water consumption range is 115×10^6-$130 \times 10^6\,m^3$ and the net benefit range is 320×10^6-370×10^6Yuan, both of them are lower than scnario 2.

The crop planting area of status quo and different scenarios are shown in Table 7. The optimization results show that:

In scenario 1, the planting area of rice, maize, and soybean increases 5%, 13%, and 10% compared to status quo. The total planting area of Hulan river irrigation district increase 6.7%, from which we can see optimization results in scenario 1 tend to plant more maize and soybean. In scenario 2, the planting area of rice, maize, and soybean increases 16%, 11%, and 11%, and total planting area of Hulan river irrigation district increase 15%, compared with status quo. In scenario 2, the increasing of rice planting area is even greater, and it may be because scenario 2 asks for more net benefit and less water saving, while rice produce more value but waste more water. In scenario 3, the planting area of rice, maize, and soybean increases 3%, 9%, and 10% compared to status quo, and amount of increase is the least of three scenarios, so as 4% of total planting area of Hulan river irrigation district.

Fig. 7 shows the crop blue and green WF under different probability. (a) and (b) are rice WF, that the value of scenario 2 > scenario 1 > scenario 3 > status quota. Rice blue WF is from 15×10^6-$113 \times 10^6\,m^3$ and green WF is from 13×10^6–43×10^6m3 in Hulan river irrigation district. (c) and (d) are maize WF, that the value of scenario 1 > scenario 2 > scenario 3 > status quota. Maize blue WF is from 7×10^6–$12 \times 10^6\,m^3$ and green WF is from 0×10^6–3×10^6m3 in Hulan river irrigation district. (c) and (d) are soybean WF, that the value of scenario 1, scenario 2 and scenario 3 is nearly the same and they are all larger than status quota. Soybean blue WF is from 5×10^6–$8 \times 10^6\,m^3$ and green WF is from 0×10^6–1×10^6m3 in Hulan river irrigation district.

3.3.3. Discussion

Using the uncertain water footprint model can get the crop water footprint distribution range, and can get the crop water footprint under the corresponding probability, providing more real and practical technical support for managers' decision-making.

For the results of optimization:

(1) At first, under different scenarios, the results of planting structure optimization are different, indicating that the needs of decision makers have a great influence on the results of the optimization model, but when the optimization results expressed in an uncertain manner, the gap between solutions under various scenarios is reduced, which can more accurately reflect the water consumption and net benefit of the entire irrigation district under the influence of random parameters.

(2) At second, from the optimization results of subarea, the total area under various scenarios has increased compared with the current situation, indicating that the increase in planting area is beneficial to the development of regional agriculture. At the same time, from the optimization results, the greatest extent of the change in the planting area of the three crops is rice, while the changes in maize and soybean are relatively small, indicating that the proportion of rice cultivation has the greatest impact on the optimization results, and should be considered in the agricultural management. From the overall net benefit point of view, in the three scenarios, the net benefit increased by 7%, 15% and 5%, respectively, indicating that the optimization results are effective.

(3) At last, at different frequencies, the gap of blue water footprint between maize and soybeans is small, <20%., which shows that in order to simplify the calculation or statistics, the maize and soybean blue Water footprint can be regarded as a fixed value, while rice needs to consider the difference in water footprint at different frequencies, because the difference in blue water footprint is 400%. Under different scenarios, the blue water footprint and the green water footprint of the crop have increased compared to the current situation, which suggests that the planting area has a greater impact on the regional crop water footprint. At the same time, the water footprints of maize and soybean between the optimized scenarios were not significantly different, suggesting that for maize and soybeans, the tendency of optimization objective may not be considered.

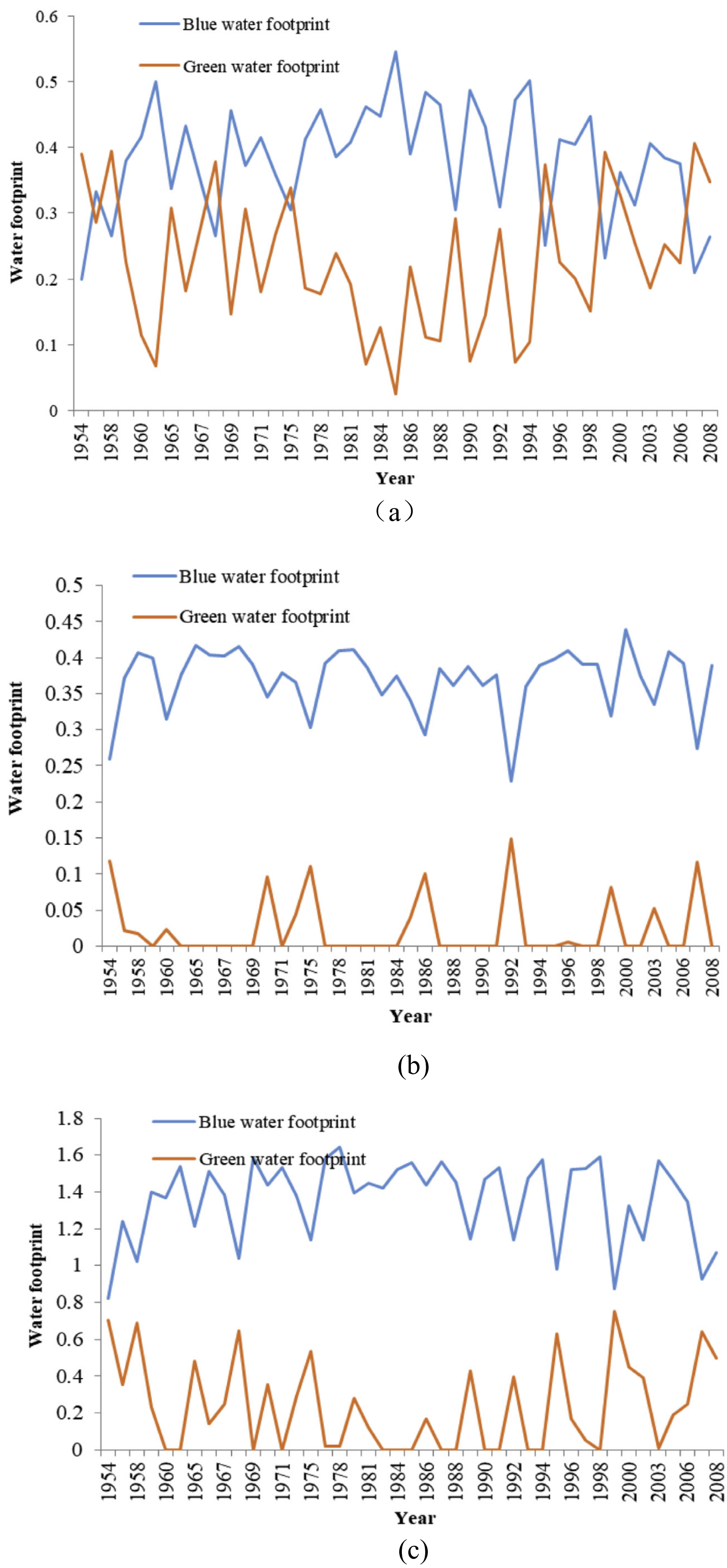

Fig. 5. Blue and green water footprint of different crops: (a) Rice(b) Maize(c) Soybean.

Table 5
Crop WF normal distribution parameters.

	Rice blue WF	Rice green WF	Maize blue WF	Maize green WF	Soybean blue WF	Soy green WF
μ	0.39	0.22	0.34	0.02	1.39	0.15
σ	0.22	0.10	0.05	0.09	0.22	0.35

Table 6
Crop WF under different probability per unit (kg/m^3).

p	Rice blue WF	Rice green WF	Maize blue WF	Maize green WF	Soybean blue WF	Soybean green WF
0.1	0.10	0.10	0.28	0.00	1.11	0.03
0.2	0.20	0.14	0.30	0.01	1.20	0.05
0.3	0.27	0.16	0.31	0.02	1.27	0.08
0.4	0.33	0.18	0.33	0.03	1.33	0.11
0.5	0.39	0.19	0.34	0.04	1.39	0.13
0.6	0.45	0.21	0.35	0.05	1.45	0.15
0.7	0.51	0.22	0.37	0.06	1.51	0.17
0.8	0.58	0.24	0.38	0.07	1.58	0.19
0.9	0.67	0.26	0.40	0.09	1.67	0.21

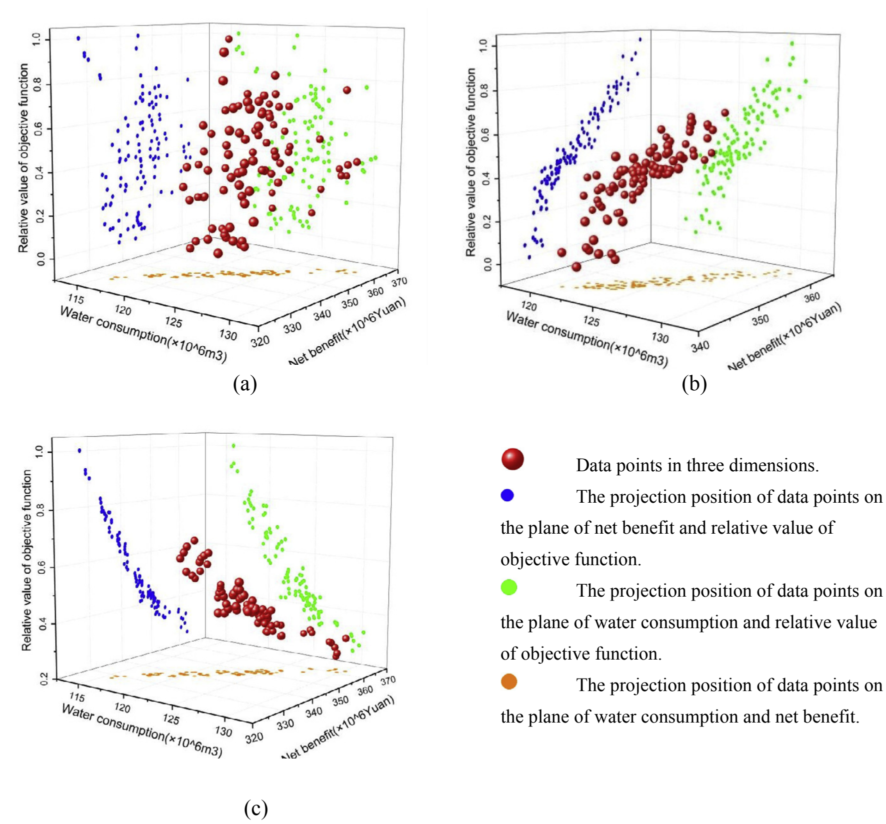

Fig. 6. Three-dimensional scatter diagram of water consumption, netbenefit and relative of objective function under different scenarios: (a) Scenario 1(b) Scenario 2(c) Scenario 3.

There are still some problems and deficiencies in this article. The optimization of crop planting structure only focuses on food crops while ignoring cash crops. For the results of model optimization, only three scenarios are considered, and adding scenarios can enrich the results. In addition, the application of the model is in the irrigation area and has not been extended to a larger area. If you can explore more about the applicability of the model, it will have a better effect.

4. Conclusion

In this paper, the uncertainty crop water footprint model was established, and the water footprint with probability distribution model of rice, corn and soybean was obtained, and the blue-green water footprint of each crop under the probability of 10%–90% was obtained. Based on the above model, a planting structure optimization model was established. The optimization model was applied to the Hulan River irrigation area, and the relationship between the

Table 7
Planting area (hm^2) and total net benefit relative value of status quo and different scenarios.

		Fengtian	Heping	Jianye	Laomo	Lanhe	Total	total net benefit relative value
Status quo	Rice	1085	6628	958	4079	2021	14,772	1.00
	Maize	275	114	24	1365	877	2655	
	Soybean	139	85	24	983	615	1846	
Scenario 1	Rice	1096	6883	1229	4238	2065	15,511	1.07
	Maize	373	124	26	1599	884	3006	
	Soybean	212	85	26	1068	642	2033	
Scenario 2	Rice	1568	7693	1367	4551	2049	17,228	1.15
	Maize	401	125	26	1499	920	2971	
	Soybean	193	94	27	1110	634	2058	
Scenario 3	Rice	1216	6677	972	4323	2056	15,244	
	Maize	291	133	29	1558	880	2891	1.05
	Soybean	215	94	30	1072	619	2030	

Table 8
Variable declaration.

WF	is the amount of water needed in crop growth stage of unit quality crop, m^3/kg
WF_{green}	is green water footprint, m^3/kg
WF_{blue}	is blue water footprint, m^3/kg
ET_{green}	is the amount of green water evapotranspiration, that is, the total amount of rainfall evapotranspiration in the field, mm/d;
ET_{blue}	is the amount of blue water evapotranspiration, that is, the total amount of field irrigation evapotranspiration, mm/d;
Y	is crop yield per unit, kg/hm^2
10	is the conversion factor that converts the depth of water (mm) into the amount of water per unit of land area (m^3/hm^2)
n	is length of the growth stage, measured with day.
ET_c	is crop evapotranspiration, mm;
CWR	is crop water requirements, mm;
K_c	is crop coefficient;
ET_0	is reference crop evapotranspiration, mm/d
Δ	is slop of the saturation vapour pressure and temperature curve; kPa/°C;
R_n	is reference crop canopy net surface radiation, $MJ/(m^2 \cdot d)$;
γ	is psychrometer constant, kPa/°C;
T	is average daily temperature at 2 m, °C;
U_2	is wind speed at 2 m, m/s;
e_s	is saturation vapour pressure, kPa;
e_a	is actual vapour pressure, kPa;
i	is area, hm^2;
j	is crop type;
f	is optimization objective;
f_1^*	is uncertain agricultural net benefit,Yuan/m^3;
$f_{1\ max}$	is maximum agricultural net benefit,Yuan/m^3;
f_2^*	is uncertain crop blue water footprint,m^3
$f_{2\ min}$	is minimum crop blue water footprint,m^3;
S_{ij}^*	is uncertain planting area of crop j in area i,hm^2;
P_j	is sale price of crop,Yuan/kg;
C_j	is cost of production of crop j, Yuan/hm^2;
Y_j	is yield per unit of crop j kg/hm^2;
Y_{minj}	is minimum yield of crop j,kg;
SA_i	is total cultivated area of area i,hm^2;
SC_j	is total planting area of crop j,hm^2;
AW_i	is total water resources available for agriculture in area i,m^3;
MA_j	is irrigation quotas of crop j,m^3/hm^2;
MW_i	is maximum water supply capacity of regional water resources in area i,m^3;
η	is utilization coefficient of irrigation water;
MGW_i	is irrigation water consumption in area i,m^3;
$WF_{blue\ j}^*$	is blue water footprint of crop$j$ in area$i$,m^3/kg;
$WF_{green\ j}^*$	is green water footprint of crop j in area$i$,m^3/kg;
a_n,b_n	is weight coefficient of optimization objectives in scenario n.

relative value of the objective function and the water consumption and net income in different situations was obtained. The comparison table between the optimal planting structure and the current situation was obtained, and different crops with different probability were obtained. Blue and green water footprint.

The results show that: (1) Uncertain water footprint model can reflect the crop water footprint under different probabilities, instead of simply using the interval form to express the water footprint of different crops, which can provide managers with more accurate information on water use. (2) The MC simulation method can overcome the limitations of traditional methods and better deal with the uncertainty parameters in the water resources optimization model of the irrigation area. The MC simulation method can effectively describe the range and distribution characteristics of

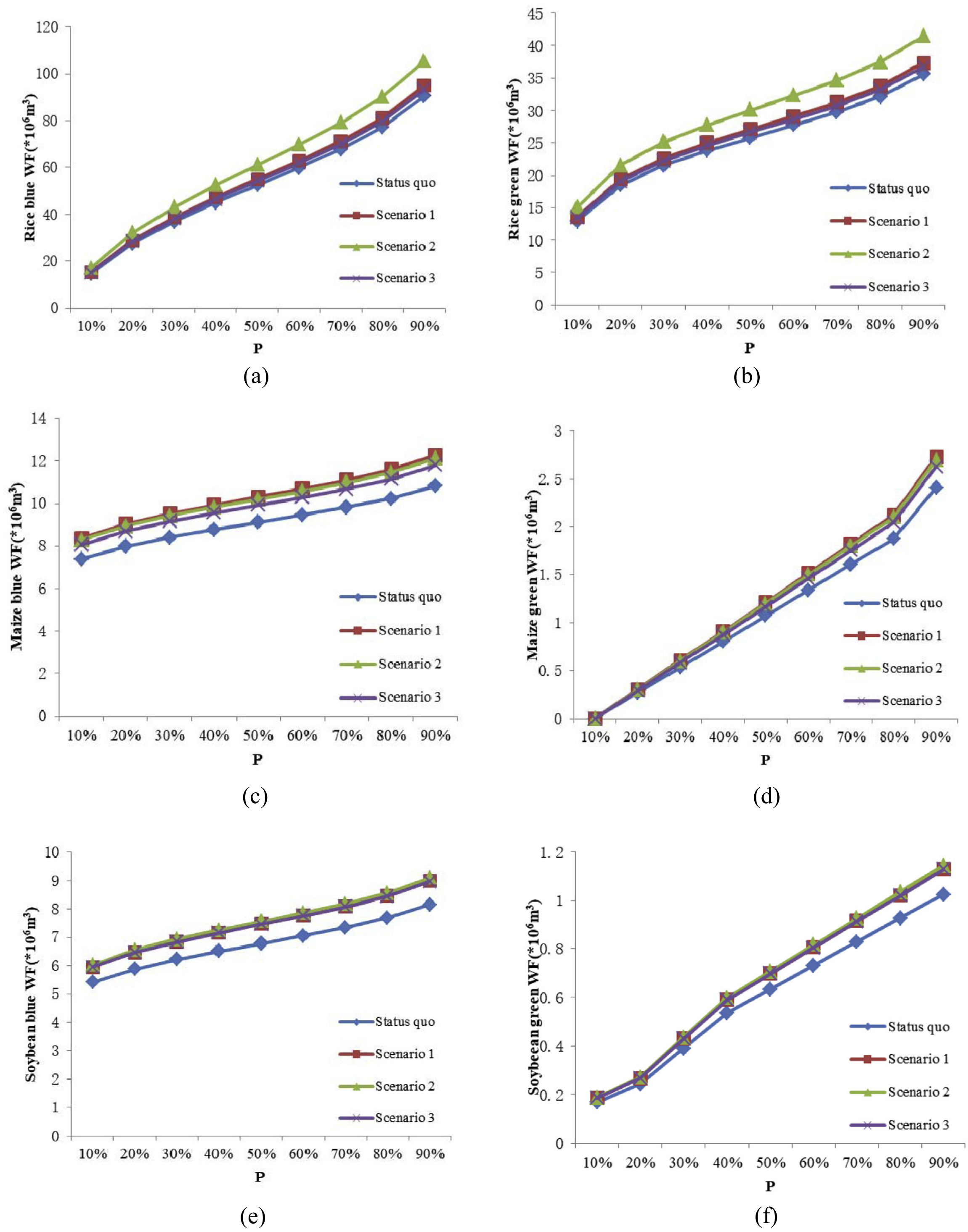

Fig. 7. Crop WF under different probability: (a) Rice blue WF(b) Rice green WF(c) Maize blue WF(d) Maize green WF (e) Soybean blue WF (f) Soybean green WF.

these uncertain parameters, and can present the optimization results in the form of probability distributions to more intuitively reflect the optimization effect and uncertainty. (3) Compared with crop planting status quo, under the premise of satisfying local food demand, taking into account the water planting structure optimization results of the water footprint, it is possible to achieve the objective of minimum irrigation water volume, maximum economic benefit and multi-objective development, and increase the efficiency of agricultural water resources utilization. The regional crop planting structure planning model considering the water footprint of uncertainty can provide theoretical basis for crop planting structure optimization and agricultural water resources management in the Hulan river irrigation area.

There are still many shortcomings about this article. The data used in the parameters in the model needs further consideration. For example, the purchase price of crops during the harvest period is related to the system revenue. The purchase price of crops before planting will affect the planting area of crops in the current season.

The purchase price of crop growth period may also affect the water allocation during irrigation, and which economic data is selected. Further research is needed as input to the parameters. Due to the many uncertain conditions in the irrigation area, the relevant models and algorithms are also diverse. In order to facilitate the promotion of research results, I think that the model and algorithm should not be too complicated. For a parameter in the model that needs to be expressed by uncertainty, a conventional expression such as an interval or a model may be used.

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